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by

Darrell E. Munson, Martin A. Molecke
Sandia National Laboratories, Albuquerque, NM

Robert E. Myers
Strategic Petroleum Reserve/DOE, New Orleans, LA

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Darrell E. Munson, Martin A. Molecke
Sandia National Laboratories*, Albuquerque, NM

Robert E. Myers
Strategic Petroleum Reserve/DOE, New Orleans, LA

ABSTRACT

A relatively large number of salt caverns are used for fluid hydrocarbon storage, including an extensive set of facilities in the Gulf Coast salt domes for the Strategic Petroleum Reserve (SPR) Program. Attention is focused on the SPR caverns because of available histories that detail events involving loss and damage of the hanging string casing. The total number of events is limited, making the database statistically sparse. The occurrence of the events is not evenly distributed, with some facilities, and some caverns, more susceptible than others. While not all of these events could be attributed to impacts from salt falls, many did show the evidence of such impacts. As a result, a study has been completed to analyze the potential for salt falls in the SPR storage caverns. In this process, it was also possible to deduce some of the cavern interior conditions. Storage caverns are very large systems in which many factors could possibly play a part in casing damage. In this study, all of the potentially important factors such as salt dome geology, operational details, and material characteristics were considered, with all being logically evaluated and most being determined as secondary in nature. As a result of the study, it appears that a principal factor in determining a propensity for casing damage from salt falls is the creep and fracture characteristics of salt in individual caverns. In addition the fracture depends strongly upon the concentration of impurity particles in the salt. Although direct observation of cavern conditions is not possible, the average impurity concentration and the accumulation of salt fall material can be determined. When this is done, there is a reasonable correlation between the propensity for a cavern to show casing damage events and accumulation of salt fall material. Interestingly, the accumulation volumes of salt fall material can be extremely large, indicating that only a few of the salt falls are large enough to cause impact damage.

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INTRODUCTION

Storage caverns have been solution mined in salt deposits throughout the world, including a relatively large number in the United States. Although the storage caverns were initially solution mined predominantly in the salt domes of the Gulf states, they are now constructed in bedded as well as domal salt deposits. These caverns provide storage for a number of valuable gaseous and fluid products of the energy and petrochemical industries. The caverns can be of various sizes, but they are typically extensive, with volumes ranging in the millions of barrels or cubic meters. When gaseous products are being stored, transfer of gas into or out of the cavern is typically through the cemented casing or rather short strings of casing. However, when liquid products are being stored, they are typically moved by displacement with brine. Handling of the brine normally involves hanging strings of casing that inject the brine near the bottom of the cavern. It appears that hanging strings of casing, regardless of the product handled, may be susceptible to damage if they extend significantly into the cavern. In some instances in fluid-filled caverns, casing in the hanging strings have been damaged or lost, even during quiescent operation [1]. Obviously, the primary concern is that the damage and loss of hanging string casing can be a significant and costly problem. However, in another sense, the hanging string damage is also of importance because it serves as a "witness gage" to events that are occurring in the cavern. These events can be partially descriptive of the interior condition of the cavern and how it is changing with time. Knowledge of the interior cavern conditions, since these are impossible to observe directly, can be of some significance in developing models of cavern behavior.

The intent of this study is to determine the relative importance of potential factors involved in the hanging string events, whether it is damage or pipe loss, then to construct a conceptual model of cavern behavior that can lead to casing damage and loss. In the process, a physical picture of the condition of caverns will be developed. First, a summary of an extensive history of events is presented for all of the Strategic Petroleum Reserve (SPR) cavern facilities. Many of these events, although not all, are thought to be related to cavern salt falls. Second, a descriptive analysis of cavern conditions is provided, giving a logical insight to the cavern behavior and the propensity for salt falls. Then, a more detailed conceptual model is developed for the primary cause of salt falls. Analogous finite element results for a simple cavern configuration are tested to determine their adequacy. Finally, the major conclusions from this study are presented.

SPR CAVERN HANGING STRING EVENTS HISTORY

The SPR facilities of the U.S. Department of Energy provide one of the most extensive hydrocarbon storage programs in the world. These facilities for storing crude oil are located in the Gulf Coast salt domes of Texas and Louisiana. Because of the unique requirements of the SPR these caverns typically operate in a quiescent condition, with little movement of the crude. Hanging string casing damage and pipe loss events have been recorded since these SPR caverns were first put into operation [1]. Damage and loss of hanging string casing is of concern because of the direct expense of replacement, as well as the indirect implications of possible cavern deterioration. The history of these caverns provides an excellent database for the study and conceptual modeling of cavern response. This database is especially valuable because it was obtained from a large number of caverns, in several domes, for liquid filled caverns operating over a considerable period of time.

The SPR Program currently maintains four cavern facilities located respectively in the salt domes of Bryan Mound, TX, Big Hill, TX, West Hackberry, LA, and Bayou Choctaw, LA. These facilities, each consisting of multiple cavern complexes, contain a total of 62 caverns [2-6]. While some 13 of the caverns were existing caverns (Phase I caverns) purchased from previous developers, the remaining 49 caverns (Phase II and III caverns) were designed and solution mined especially for the SPR project. The purchased caverns are each unique, usually irregular in diameter, size, and depth. However, careful solutioning practice during construction of the SPR purpose-built Phase II and III caverns led to remarkably similar shapes and sizes, typically roughly cylindrical caverns 2000 ft high by 200 ft in diameter. Also, depths to the cavern roofs in these caverns in the salt dome are all about 2000 ft; hence, the stress fields are nearly identical. Construction of these caverns extended over several years, predominantly between 1980 and 1991 [2]. The caverns were filled with crude oil immediately after initial solutioning, and sometimes even during the later stages of solutioning, and thereafter operated primarily in a quiescent condition. While all caverns contain at least one hanging string of casing extending to near the full cavern depth, some caverns may contain multiple hanging strings of various lengths. Quiescent operation has been interrupted in some caverns only for trial oil pumping demonstrations, limited oil sales, and oil degassing operations. Typically, these interruptions require oil transfers that are accomplished using raw water displacement with some accompanying additional solutioning. However, a more typical interruption of quiescent operation occurs during cavern depressurization to accommodate damaged hanging string workovers. During such depressurization, little oil transfer occurs.

From the time of construction completion, many of these caverns have experienced events which resulted in damage and frequently loss of casing from the hanging strings. Prior to November 1997, the time period covered by this work, a total of more than 33,435 ft of casing has been lost. Damage or casing loss is normally detected either by the appearance of oil in the site brine pond, when the damage is above the oil/brine interface, or by wireline tests which show obstructions or loss of pipe. In each instance, a workover to replace the hanging string is required. A frequency chart of all events prior to November 1997 is given in Figure 1. Over the nearly 17 year history of the SPR program covered here to date, the Bryan Mound facility has the greatest event propensity, with 54 events and 43 string failures, followed by West Hackberry, with 11 events and nine string failures, Bayou Choctaw, with five events and two string failures, and then Big Hill, with one event. There is no indication from the frequency chart that the events are increasing with time. In fact, there appear to be no significant trends observable. It must be noted again that the database is very sparse.

Although event records are available, the causes of events are not always clear. The events have been categorized according to (1) those where impact damage is clearly identified and thought to be the result of salt falls, (2) those where the damage is not definite, but could potentially be the result of impact damage, and (3) those which apparently do not show impact damage and cannot be attributed to salt falls [7]. The latter events may be operationally induced during workover of a cavern well. Because workover procedure faults can be remedied through other means, the focus of this study is limited to those events thought to be the consequence of salt falls. Other factors that potentially can contribute to these events must be analyzed. When the event of damaged or casing loss is identified and the casing string is recovered (pulled) from the cavern, examination of the recovered casing is sometimes instructive. In many instances the casing shows a distinct impact abrasion and indentation, which is coupled with a general bending that extends over several joints of casing [8]. Additional instability folding and separation of joint couplings may also occur during the recovery of the casing string. From such evidence, it is often logical to conclude that the initial damage was the result of an impact from a falling mass of salt. However, the lack of impact evidence on some recovered strings suggests the possibility of other causes of casing damage.

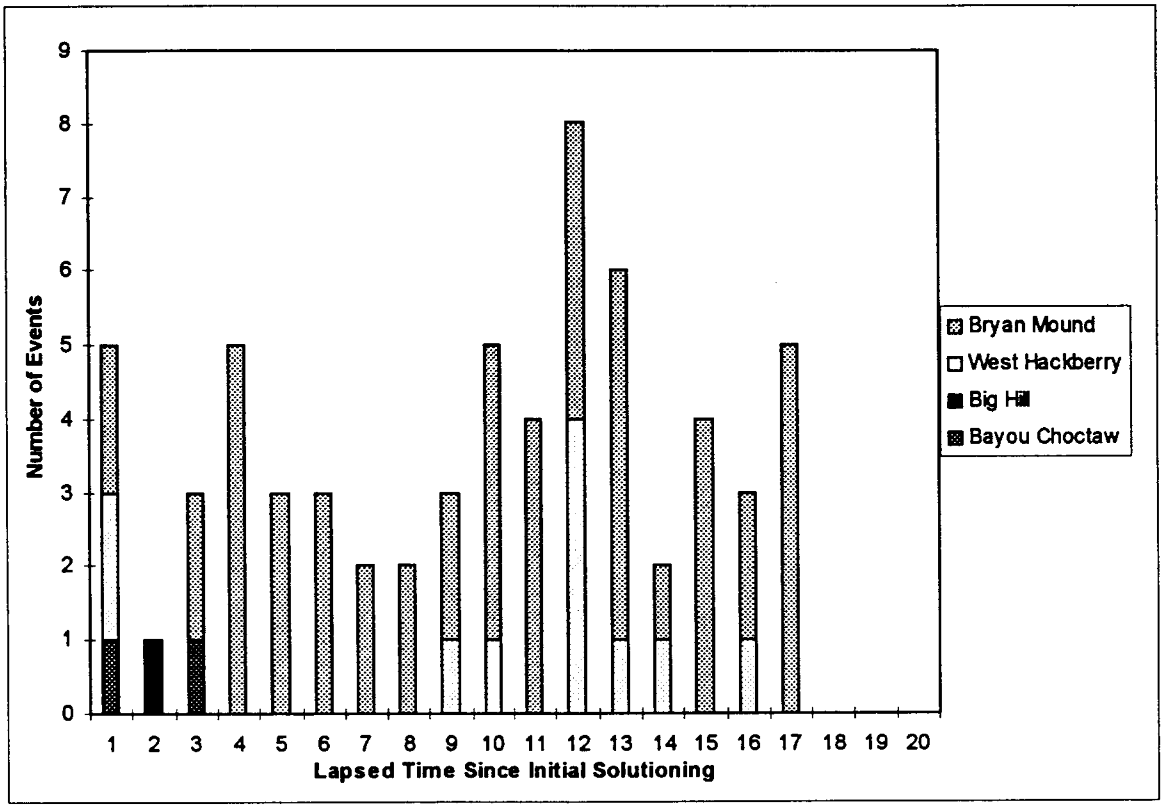

Figure 1. Distribution of Hanging String Casing Damage and Loss Events in the SPR Caverns [1].

A theoretical study of the dynamics of falling slabs in a somewhat viscous oil media has been made by Ehgartner [9]. For the very ideal situation of a very thin slab falling edge-wise, it was determined that a slab 1 x 5 x 5 ft would attain a velocity of 40 mile/hr within 150 ft, and attain a velocity of 130 miles/hr after 2000 ft. Even though the slab dimensions that we have assumed here are relatively small, this mass of salt is equivalent to a small automobile. Such a slab can and would impart significant impact energy to the casing. Clearly, in a less than ideal situation, such as an oscillating or "falling leaf" mode, the vertical velocities would be less, with possibly a lessened impact. On the other hand, very small particles would probably fall at the other extreme of velocity, settling at a very slow rate.

On the basis of the potential impact velocities, one would readily suppose that at least some salt falls could readily cause the observed impact damage to casing strings. In fact, Munson [8] has suggested a scenario based on impacts of a salt mass and subsequent string removal activities to explain the several different forms of damage observed.

In an extensive study by the authors [1], the factors that could potentially cause damage and loss of pipe were evaluated in considerable detail, and are summarized in Table 1. These factors include both natural and operational factors. Natural factors are those related to salt dome features, such as the postulated occurrence of anomalous zones (zones of shear, impurity concentrations, etc.) traversing the entire dome, and material response characteristics (salt creep and fracture). Operational factors include those related to construction (cavern geometry, number of wells involved in solutioning, and cavern location within the dome) and to operation (crude type, cavern pressure, and depressurization during workover). We will not repeat the logic in the evaluation [1] of the various factors, but will provide the results. On the basis of the logic of the study, it was concluded that operational factors could not be the primary factors in causing events, except in those recognized instances of workover or operational practice inadequacy previously excluded from the study. The natural anomalous features of the domes could also not be a primary factor. However, natural material response characteristics were found to be the most likely primary contributors to the production of salt falls, and hence, to damage and casing loss. Material fracture, as influenced by local impurity concentrations, is thought to explain the fact that the caverns in some domes, and the individual caverns within a given dome, have a higher propensity for events. On the basis of this logic, we develop a model for salt fall generation.

Table 1. Major Factors Considered in Evaluation Process [1].

Factor	Condition	Application	Comments	Cause
Anomalous Zones	Natural	General	Possibly a secondary factor.	Secondary
Crude Type	Imposed	General	Possibly a secondary factor.	Secondary
Leaching Method	Imposed	Local	Linked to geometry irregularities.	Secondary
Operating Pressure Depressuring Cycling of Crude	Imposed	Local	Linked to stress.	Secondary
Location in Dome	Imposed	Local	Cavern spacing, dome edges.	Secondary
Cavern Depth	Imposed	Local	Linked to stress magnitude.	Secondary
Cavern Geometry	Imposed	Local	Roof span, geometry irregularities.	Secondary
Creep Properties	Natural	General/Local	Deformation processes.	Secondary
Fracture Properties	Natural	General/Local	Salt fracture, link to impurities.	Primary

ANALYSIS OF CAVERN CONDITION

Relevant information can be obtained from close analysis of available hanging string event data. This information concerns the potential vertical distribution of the events and hence the possible distribution of salt falls, as well as information about the relative quantities of salt falls.

First, the relative frequency of events as a function of depth in the cavern can be determined and is shown in Figure 2. This is just the hanging string length in feet after subtraction of the casing loss. This is a rather unusual plot in that it represents overburden depth against the length of casing above the point of casing damage. It presumably should be a straight line at 45^0 with an intercept on the abscissa equal to the depth of the cavern roof. The plotted information indicates that no significant impacts occur in the top quarter of the caverns. Also, the greatest concentration of impacts is in the lower half of the caverns for all sites except the single event reported for Big Hill (BH). This perhaps suggests that generation of salt falls is a function of overburden depth, as would be supported by the strong dependence of creep on the depth (stress). Somewhat surprisingly, Bryan Mound, which has the greatest number of events, is actually one of the shallower facilities, and hence, the stress levels should not be quite as great as those in the other facilities. Obviously, a factor other than simply the creep stress is involved.

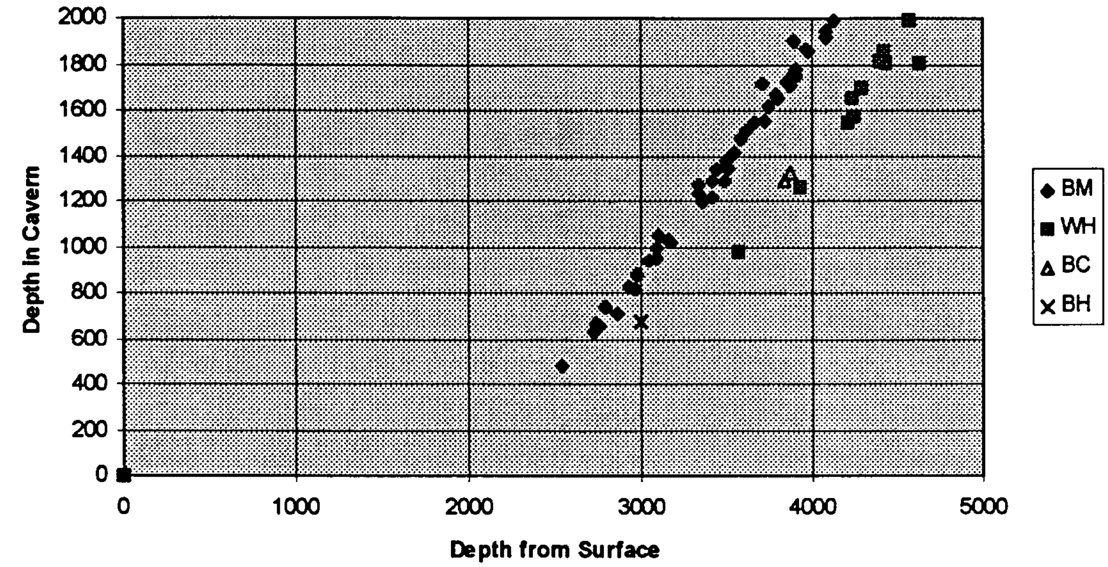

Figure 2. Relative Depth of Events as Determined from Remaining Hanging String Lengths.

There is another important piece of information that can be gained from available operation data [1]. It is possible to deduce the amount of salt accumulation in a cavern during quiescent operation. The operator routinely obtains wire line surveys of the cavern to locate the depth of the oil/brine interface, casing length, and cavern bottom. The cavern bottom depth is obtained by "tagging" and, therefore, the change in depth because of salt accumulation can be measured as a function of time. Additional information, which can be used to determine the size and geometry of the cavern bottom, is obtained from sonar surveys taken at the end of cavern solutioning. The volume of salt accumulation can be calculated from these data. Because of the relatively large uncertainty in the sonar data and the approximations necessary to calculate volumes, the volume accumulations could be in error perhaps by as much as a factor of two. Even with this uncertainty, however, the relative values should be instructive. Because the accumulated salt is porous, a 55% bulking factor, which is the theoretical packing density of particles, correction has been made to obtain a true amount of fallen salt. For our purposes here, we will restrict the analysis of salt accumulation to the Bryan Mound facility. Table 2 lists the caverns in order of the accumulation rate of salt. As is apparent, the caverns show a range of accumulation rates, some with rates that are extremely large. Cavern BM112 shows an accumulation rate of nearly 10,000 tons per year. Even given the potentially large uncertainty in the accumulation amount, the implication is still that this cavern must be losing an extremely large amount of salt from its walls. The ranking of caverns by the salt fall accumulation amounts together with corrected event numbers (essentially taking only the hanging string with the greatest number of events in multiple string caverns) show a reasonable correlation between salt fall amount and casing damage events. In fact, the large amount of salt fall accumulation, the correlation to string events, and the visual evidence of casing damage are very strong support for the concept of salt falls being one of the primary contributors to many of the events of casing damage and hanging string pipe loss. However, the significant amounts of accumulation in comparison to the relatively small number of impact events sufficient to cause casing damage strongly indicates that the general spall size of any salt fall is quite small. Apparently, only a few of the spalls are massive enough to cause damage.

Table 2. Calculated Salt Fall Accumulations and Insoluble Contents of Bryan Mound Caverns

Cav.	Dia.Bot.	Dura.	Acc.	Fall Vol.	Number of Events			Cav.Vol.	Insol.Vol.	Insol. %
	ft	yrs	ft/yr	tons/yr	Total	Wells	Corrected**	ft^3x10^6	ft^3x10^6	vol. %
112BM	200	11	8.5	9840	5	5A	5	62.20	3.56	3.2
109BM	260	13	3.6*B	7043	4(-1)	1A,2B	2			?***
103BM	170	12	6.0	5018	4	4C	4	63.74	5.71	4.9
106BM	130	13	10.1	4939	10	4A,6C	6			?
107BM	180	13	3.0*C	2813	7	4A,1B,2C	4			?
113BM	180	10	2.3	2157	1	1B	1			?
114BM	170	9	2.0	1672	0		0			?
105BM	240	13	0.5	833	0		0	64.09	6.17	5.3
111BM	160	12	1.0	714	1	1B	1	63.20	3.91	3.4
101BM	200	12	0.6	695	1(-1)	1C	0	63.20	6.30	5.5
110BM	90	14	2.4*A	563	0		0		1.39	?
108BM	200	11	0.4	463	4(-2)	2A,2B	1	63.01	4.775	4.2
115BM	150	10	0.7	456	0		0			?
104BM	160	13	0.2	148	0		0			?
102BM	95	12	0.3	78	2(-1)	2B	1	79.67	1.42	1.0
Insufficient data to determine conditions for the following cavern										
116BM		10	2.0		2	2B	2			?

* Only one well (as noted) was used to determine the increase in accumulation depth in these caverns.

** The correction includes subtraction of events that occurred during solutioning (-n) and, in multiple well caverns, taking the well (underlined) with the maximum number of events as the single well figure.

*** Not all caverns had sufficient sonar data to determine the sump size, so the calculation of insoluble percentages were not possible.

It is reasonably clear that we can draw some other significant conclusions from the above analyses. First, the marked variation in the quantities of salt accumulation in the caverns in the Bryan Mound facility suggest that the conditions of individual caverns differ significantly. When the potential primary factors were initially examined, it appeared that all factors were at best secondary, except for the material response. Since the material response could not be examined directly, it remained a candidate as the dominant factor. It appeared that the material creep and fracture characteristics, which are strongly dependent upon local impurity content, could vary between caverns and facility sites. This would explain, indirectly, the variation in the amount of salt fall material. This also would explain, conceptually, the observed variation in casing damage events between these same caverns and sites.

In theory, it is also possible to determine the quantity of insolubles (impurities) released during the solutioning of the cavern. The volume, and hence the amount of removed salt mass, of the caverns is well known from either volumes calculated from sonar surveys, volumes and brine contents of solutioning water used, or volumes of crude oil emplaced. Typically, these independent figures roughly agree. It is also possible from successive sonar surveys taken during sump formation to calculate the sump size, which when taken with the depth of the insolubles deposited in the sump gives the amount of insoluble material. It is then relatively easy to determine the volume insoluble content in the original salt mass. Unfortunately, insoluble contents calculated in this manner are not very accurate. There are several reasons for this uncertainty, with the difficulty in determining the early sump shape perhaps the most critical. In addition, as opposed to the calculations described previously of salt accumulation which are relatively insensitive to the uncertainties in shape, the calculations of impurity content are strongly affected by these same uncertainties. As a consequence, the stated impurity contents could vary by more than a factor of two. As shown in Table 2, a factor of two in the impurity levels could alter significantly the rank order and make it difficult to assess the caverns according to an impurity criterion. Never-the-less, the impurity levels calculated are certainly within a reasonable range for domal salts.

CONCEPTUAL MODEL OF FRACTURE AND SPALL FORMATION

After analysis, we believe that all the factors except the material response of creep and fracture can be logically defined as secondary. Simple logic cannot currently define the creep and fracture response as either secondary or primary, and, as a result, a more detailed analysis is required. It is now necessary to introduce a conceptual model of salt fall formation. This conceptual model is based on the known creep and fracture behavior. As the analysis of factors suggest, the propensity of a cavern to exhibit salt falls depends upon location in a dome as well as the specific dome. Thus, the factor controlling the salt fall propensity must be a local factor. This local factor must cause differences in the creep and fracture response among the various domes and caverns. In addition, the details of the model must account for the great accumulation of salt fall material, most of which is of a size incapable of damaging a hanging string.

In proposing a conceptual model of fracture and spall formation, we can draw upon a considerable body of constitutive modeling. These constitutive descriptions were initially developed for the Waste Isolation Pilot Plant (WIPP) Program to describe the creep and fracture of salt [10-12]. They were applied to the bedded salt formation of the WIPP site to predict structural response of underground openings. One of the characteristics of the fracture model is the strong dependence of fracture on the impurity content of the salt; conversely, the creep response is only weakly linked to impurity content. In fact, a few percent of impurities was found experimentally to markedly enhance the fracture of salt, and this effect was incorporated into the constitutive description of fracture to form the Multimechanism Deformation Coupled Fracture (MDCF) model [11]. In the MDCF model, the individual particles that make up the impurities cause the local stress field to change in such a manner as to enhance the formation of microfractures in the salt. It is neither possible nor necessary to give the complete MDCF model development here. However, the relevant equations to illustrate the effect of pressure and impurities on fracture will be presented. The stress that controls the fracture process is the power-conjugate equivalent stress for microfracture formation. This equivalent stress is given by [11]

$$\sigma_{eq}^{\omega_s} = \left|\sigma_1 - \sigma_3\right| - f_p x_2 x_7 \operatorname{sgn}(I_1 - \sigma_1)\left[\frac{I_1 - \sigma_1}{3x_7 \operatorname{sgn}(I_1 - \sigma_1)}\right]^{x_6} \tag{1}$$

where the first term in the right-hand-side of Eq. 1 is the difference in principal stresses given by $|\sigma_1 - \sigma_2|$, or the Tresca maximum shear stress criterion. The second term in the right-hand-side of Eq. 1 essentially describes the confining pressure as the first invariant (I_1) minus the first principal stress (σ_1) and various constants, χ_2, χ_6, and χ_7. Here sgn ( ) is the signum function and the function, f_p, defining the influence of impurity particle or porosity void sites, as given by

$$f_p \cong 1 - p_1 \rho \tag{2}$$

where p_1 is a constant and ρ is the volume fraction of impurities or voids in the salt. Numerical values for the constants in these equations have been determined for a bedded salt material, both clean and argillaceous, of the WIPP [11].

Under normal conditions, the strong influence of the lithostatic pressure, expressed through the complicated second term on the right-hand-side of Eq. 1, causes the term to increase, which diminishes the equivalent stress, and hence suppresses the formation of microcracks. However, the effect of impurities is to cause the value of the second term to diminish, and in fact may cause it to become zero, as the particle volume fraction increases.

The proposed model indicates that during the creep closure of the caverns, salt can also undergo concurrent material damage by microfracture formation. Although the model is not capable of handling discrete fractures, it is known that this microfracture material damage can lead to discrete fracture of the salt, and eventual spallation to form a salt fall. Because the amount of creep and the extent of material damage is related to the stress (roughly, σ^5) in the salt, the material damage, and hence, fracture and spall, would be expected to increase with depth in the cavern and the depth of the cavern in the dome, and to decrease with the operating pressure. While the database is too sparse to observe these suspected trends in detail, it is clear that hanging string damage and failure is greater with depth in the cavern, as shown in Figure 2. But, it is also clear that Bryan Mound, which has the greatest number of events, is comprised of caverns that are located at somewhat shallower depths than the other caverns, contrary to the simple expected trend. This indicates again the fact that the primary factor is probably related to be behavior of materials, i.e., impurity content.

Unfortunately, at this time we have no way to accurately judge the impurity content of a cavern, much less the variation of impurities throughout a given cavern. Never the less, we can make some simple assumptions and use the MDCF constitutive descriptions of creep and fracture to determine what conditions would likely reproduce the observed salt fall results. This is the beginning of the definition of the interior condition of a cavern.

SIMPLE CONFIGURATION SIMULATION

The intent of the model simulations is to show the influence of various parameters on the propensity for the development of material damage, as a precursor to fracture and spall. A set of simulations has been published for a situation that matches, although does not duplicate exactly, the conditions of interest to us. Munson et al. [13] reported the use the MDCF model of creep and fracture for the simulation of an open shaft at a depth of about 2100 ft. The simulation was to determine the amount of material damage and fracture induced in a uniform radius and smooth walled shaft at a time of about 50 years. An overburden stress was applied, as was an internal pressure approximately equivalent to a head provided by internal fluid fill, in this case it was zero. The cavern is excavated at time zero. Parameter values for the simulation are those determined for the argillaceous (impurity containing) and clean salt of the WIPP [11]. It was found that simulations using clean salt parameters did not create any damage at any level in the shaft. However, the influence of impurities was demonstrated in another simulation using a 2.9 % by volume value of impurity content for the same general configuration. With the impurity, the simulation showed that damage was created in the shaft wall. The damage is maximum at the shaft wall and diminishes markedly with distance into the salt. Even in this simulation, the calculated damage was still rather small, being only about 0.0005 at the shaft surface. When this calculated damage value is compared to the value of damage of 0.15 necessary for salt failure, it is apparent that the shaft wall is relatively stable. To generate greater damage values would require either a greater shaft depth, or longer times.

These results are essentially confirmed by more recent calculations for the design of a shaft seal for the WIPP Program [14]. Here the potential damage at the 2060 ft depth was shown to exist but to again be comparatively small.

A summary of the above simulation results suggest that a model based on the influence of impurities in salt to increase the propensity for the formation of microfracture damage is not really sufficient. While the impurities do markedly increase the propensity for microfracture damage, the calculated damage levels are too small to produce failures. In addition, the simulations are for a smooth-walled cylindrical configuration that produces an inherently stable monotonic damage-distance relationship which cannot produce a spall mass. The monotonic relationship can only lead to sloughing of the wall.

Even though the SPR caverns have not been specifically modeled, it is possible to apply the above results to some of the caverns of the SPR. Those Phase II and III caverns that were constructed specifically for the SPR all had the same general cavern dimensions and shapes. While they are roughly cylindrical, there are caverns with geometric irregularities. They all have cavern roofs at 2000 to 2300 ft below ground surface and have heights of some 2000 ft. The bottoms of the caverns are therefore about 4300 ft, at the maximum, with lithostatic stresses comparable to this depth. In normal operation, however, the caverns are filled with crude oil that has a fluid pressure gradient which acts to oppose the lithostatic pressure. In fact, the unpressurized fluid filled cavern condition produces pressure differences at the cavern bottom almost equivalent to those in an empty shaft at half the depth. Thus, the cavern stress condition is essentially the same as those simulated in the WIPP shaft calculations given above. As a result, we may conclude that, under that assumption of smooth cavern walls, the damage levels will be insignificant, even at the bottom of the cavern where the stress conditions are the most favorable for development of damage, unless the salt contains impurities. However, even then, the material damage level and configuration are insufficient to cause spall formation in a smooth walled cavern under typical operation conditions. Some other feature is necessary to produce regions of greater material damage.

We suspect that the additional feature must involve a geometric configuration. Because the major geometric differences in cavern shape was eliminated in the earlier study [1] as a principal factor in casing damage events, the geometric configuration effect must be either very specific or more subtle. In either case, the additional feature is not a fundamental inadequacy in the constitutive model. The constitutive model contains sufficient detail to cause selective damage as a function of the impurity content of a cavern. Undoubtedly, the necessary additional feature is probably comparatively small geometric irregularities in the cavern walls at a scale much smaller than the cavern dimensions. It appears essential to introduce this type of initial geometric configuration into the calculation. In fact, it is known that the walls of the caverns are irregular on a small scale and we now believe that such irregularities are necessary for the creation of spalls. Such geometric configurations do not alter the fundamental model because they would be influenced by impurity content in the same manner as a smooth walled cavern making impurity containing irregularities more prone to spalling. However, a significant difference does occur in the case of the surface irregularity because the stress fields are no longer simple and stress concentrations may occur. The behavior of irregularities in the cavern wall are too complicated for presentation here, but are the subject of future study and will be incorporation into the model of spall as appropriate.

DISCUSSION AND CONCLUSIONS

In many instances, it is not possible for the operator to know or directly observe the response of a cavern in detail. In recent years, however, knowledge of cavern behavior has improved considerably. In fact, it has now become accepted that the cavern can slowly lose volume due to the creep closure and that this closure must be taken into account during operation. In some caverns, fluid extraction is necessary to maintain a constant operating pressure, which is a measure of the creep effect. As the ability to calculate cavern creep closure has become better developed, creep models have been used to develop an operational tool for continuous determination of cavern well integrity [15].

However, there are other cavern responses that do not change the effective volume even though they reflect changes in the cavern conditions. One of the most important is the spalling of wall surface material to cause salt falls. We address how caverns deteriorate as a function of time through loss of surface material in this study. A direct indication of possible deterioration is thought to be the damage and loss of hanging strings because the casing acts as a "witness gage" to salt falls from the roof or sides of the cavern. While hanging string damage is possible in either gas or fluid filled caverns, it is more likely in fluid filled caverns where the transfer of fluid is by brine or water displacement through a hanging string. Gas storage normally does not require hanging strings.

The casing damage and loss events were documented for the SPR caverns [1]. Although not all of the events can be attributed to salt falls, many of the recovered strings showed the damage pattern consistent with impacts of massive falls. Because the salt domes of the Gulf Coast contain no lenses of anhydrites or other non-salt materials, the falls are thought to be composed primarily of salt. Moreover, the salt is known to contain significant impurities and it is these locally distributed impurities that may explain the marked differences between caverns of a given dome, or between the several domes, to exhibit salt falls. Since a salt fall does not alter the volume of the cavern, the question was how to determine the cavern conditions. There are, fortunately, some methods to determine relevant information about salt falls. In those quiescent caverns that are routinely tested by wireline, the cavern bottom elevation is often determined by "tagging." If the bottom elevation continues to rise with time, this is an indication that material is accumulating, material that is probably due to salt falls. By making correction for the bulking of the fallen material, some indication of the amount of salt in the salt falls can be obtained. As we have seen, the amount of fallen material can in some cases be quite appreciable. Several other interesting observations can also be made. It is reasonably clear that the majority of the salt falls masses must be rather small, if they were not, no hanging string could survive even briefly for a cavern such as BM112 with 10,000 tons/year salt fall accumulation. Infrequently, a spall mass of a larger dimension must fall, with these most probably causing the observed casing damage.

A conceptual model of salt fall is proposed based on a constitutive model of creep and fracture. This model has as one of the variables the amount of impurity or inclusions in the salt, with the higher impurity contents producing greater levels of microfracture damage. In order to test the model, previously published simulations of a very simple shaft configuration, one with smooth sides, were compared. By analogy, a simulation of a shaft using clean salt suggests that no wall fracture will take place in a oil or brine filled cavern, even at a cavern depth of 4000 ft while operating in the depressurized, hydrostatic internal pressure, condition. A similar shaft simulation, using an impurity content of 2.9% showed some, but still very little damage in a shaft, which by analogy is again equivalent to a brine or oil filled cavern at the 4000 ft depth. Here, as expected, the fracture damage is always maximum at the wall surface and diminishes with distance into the salt, indicating than only sloughing, without spalling, would most probably occur.

These results suggest that even though the effect of impurities is to increase the amount of damage, the total damage in a smooth-walled simulation remains rather small. In addition, the distribution of the damage in a smooth-walled simulation does not suggest formation of salt fall spalls. As a result, a simple materials based model of response is not entirely adequate. In order to produce spalls of significant mass, it seems necessary to have surface irregularities in the cavern wall. These irregularities must be on a scale considerably smaller than the scale of the caverns because the known large scale irregularities of the caverns were shown [1] not to be a principal factor in determining the casing damage events. The influence of impurities on the accumulation of damage in such surface irregularities would be the same as in the smooth-walled cavern simulations except for the possible damage enhancement from possible stress concentrations. The impurity levels would enhance the damage effects, leading to the formation of spall masses. Investigation of such irregularities, and their consequences, is just beginning and will be the subject of future studies and model development.

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